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**BRISTOL BAY SOCKEYE SALMON PRODUCTION: AN EXPLORATORY
ANALYSIS OF THE 1996 AND 1997 DECLINE IN SOCKEYE SALMON RETURNS**

by

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ABSTRACT

Sockeye salmon forecasts developed for Egegik, Naknek, and Kvichak Rivers in Bristol Bay, Alaska contained large forecast errors across river systems for 2-ocean returns in 1996 and all age classes for Naknek and Kvichak in 1997. The forecast models include univariate and multivariate time series analysis models that incorporate returns (catch + escapement from 1956 to 1995), return-escapement, sibling, and smolt relationships. Marine environmental influences were included in multivariate time series models when significant cross-correlations between the residuals from the forecast models and residuals from the univariate environmental models occurred. A persistent significant relationship between sockeye salmon returns and the annual anomalies of mean (May - August) air temperatures taken at Cold Bay, Alaska (CBMAT) lagged by 1, 2, or 3 years was found. The best model and forecast statistics for 2-ocean sockeye salmon consisted of age class returns (1.2 and 2.2) that included CBMAT, whereas, sibling models produced the best model and forecast statistics for most of the 3-ocean sockeye salmon return time series. The only exceptions were for age classes 2.2 and 2.3 in Kvichak where the linear transfer function smolt model and univariate model of returns produced the best overall model and forecast statistics, respectively. Including Cold Bay, Alaska air temperatures did not improve forecast performance in 1996 or 1997. Sibling relationships improved forecast performance in 1997, particularly for 3-ocean sockeye salmon returning to the Egegik River.

INTRODUCTION

It has become increasingly apparent that variation in the marine environment contributes greatly to Pacific salmon (*Oncorhynchus* spp.) population variability (Francis and Hare 1994; Beamish and Bouillon 1995; Hare and Francis 1995; Mantua et al. 1997). Some of this variability is due to low frequency changes in salmon populations with periods of low or high abundance that may span decades (Hare and Francis 1995). Given the importance of decadal changes in salmon populations, many of the proposed Pacific salmon production models now include parameters related to causal mechanisms of large scale physical changes in the environment of the North Pacific Ocean. However, the scale of inter-annual variation is also large -- returning adult salmon to a river system commonly vary by more than an order of magnitude between years -- making it important for managers of these stocks to prepare annual preseason forecasts of the allowable catch for each stock.

To help explain the large inter-annual variability in adult salmon returns, managers often incorporate biological relationships in their models. Stock-recruitment models are commonly used, due to the importance of escapement to adult salmon returns, but may be of limited benefit as escapement usually explains little inter-annual variation in adult salmon returns (Peterman 1987). Other biological relationships such as early marine growth rates, abundance of smolt, abundance of a cohort returning the previous year have been useful, at times, in explaining inter-annual variation in adult salmon returns.

When biological relationships fail to explain inter-annual variation in salmon returns, managers often include environmental variables in their analyses. Variables characterizing ocean conditions during the first few months in which juvenile salmon encounter marine water are

particularly important, as that period is believed to significantly act on inter-annual variability in salmon survival and growth (Pearcy 1992). Climatological factors impacting the marine environment and possibly affecting salmon production include localized variables such as air temperatures and sea surface temperatures (Quinn and Marshall 1989; Adkison et al. 1996) and basin scale climatic variables such as the El Nino-Southern Oscillation Index (SOI) and the Aleutian Low Pressure Index (ALPI), which may affect biological production in the North Pacific Ocean (Mysak 1986; Beamish and Bouillon 1995).

Sockeye salmon (*Oncorhynchus nerka*) returns (catch + escapement) to Bristol Bay, Alaska have fluctuated greatly over the last 42 years. Decreasing and increasing trends within the data series are punctuated with large year-to-year variations (Figure 1). During the early 1990s, Bristol Bay sockeye salmon returns reached record levels; however, returns of sockeye salmon to Bristol Bay fell during 1996 and then plummeted during 1997 producing less than half of the expected return. This dramatic decline in sockeye salmon returns has sparked renewed interest in explaining and modeling the possible underlying mechanisms responsible for the large inter-annual variability in Bristol Bay sockeye salmon returns.

In this paper, we examine three river systems in Bristol Bay (Egegik, Naknek, and Kvichak) by analyzing the relationships of biological mechanisms such as escapement, smolt outmigration, and sibling relationships, and environmental mechanisms such as sea surface temperatures, air temperatures, and basin-scale climatological variables (e.g., SOI and ALPI) to adult sockeye salmon returns. The objective of this study was to determine if these biological and environmental mechanisms could explain the rapid decline of sockeye salmon returns to Bristol Bay, Alaska during 1996 and 1997.

MATERIALS AND METHODS

We used time series analysis to model sockeye salmon returns for its ability to account for autocorrelation in the return data (Noakes et al. 1987) and for its utility in forecasting salmon production (Quinn and Marshall 1989; Noakes et al. 1990; Marshall 1992; Farley 1996). Model performance was evaluated based on the percentage of the variation explained in the sockeye salmon return data, the residual standard error, and Schwartz's Bayesian Information Criterion (Schwartz 1978, Adkison et al. 1996), a model selection criterion which penalizes highly-parameterized models. Model performance was also evaluated based on percent error for forecasts of 1996 and 1997. This approach allows us to postulate the degree of influence of biological and environmental mechanisms on inter-annual returns of sockeye salmon in these three river systems.

Time series of sockeye salmon data

As indices of sockeye salmon productivity, we used: (1) total returns (catch plus escapement) for age classes 1.2, 1.3, 2.2, and 2.3 (see Koo 1962 for age class designation) from the Egegik, Naknek, and Kvichak Rivers of Bristol Bay, Alaska for years 1956 - 1997; (2) escapement data (1956 - 1997) for each river system; and (3) smolt data from the Kvichak River for years 1976 -

1997 (Bev Cross, Alaska Department of Fish and Game, Anchorage, AK, personal communication). Emphasis was placed on these three river systems because they have constituted over 70% of the total returns to Bristol Bay since 1984. We also calculated returns per spawner (total escapement to river system) for each age class for brood years 1956 - 1989 (age class 2.3), 1956 - 1990 (age classes 1.3 and 2.2), and 1956 - 1991 (age class 1.2) as another measure of productivity to be used in univariate and stock-recruitment models. All data were log-transformed to stabilize variance; catch, escapement, smolt counts, and return per spawner data tended to have skewed distributions and variance increased as the mean increased.

Time series of environmental data

Environmental influences on sockeye salmon returns were examined for effects on survival during marine residence. Marine environmental factors possibly related to sockeye salmon survival included regional and basin-scale climatological conditions. Regional climatic conditions included air temperatures from April through June and May through August, two periods that possibly affect growth and migration through Bristol Bay and along the Alaska Peninsula respectively (Straty and Jaenicke 1980). We used air temperatures for April through June taken at the King Salmon, Alaska monitoring station (KSAJT) and May through August taken at the Cold Bay, Alaska monitoring station (CBMAT) as a surrogate for sea surface temperatures in Bristol Bay and along the Alaska Peninsula, because sea surface temperatures for these areas were not available. All air temperature data were obtained from the US National Climate Data Center. We averaged monthly data, then calculated standardized values of each time series by subtracting the mean and dividing by the standard deviation for each observation (Figure 2).

Basin-scale climatological conditions included Bering Sea surface temperatures (BSST) and also SOI and ALPI, two indices mentioned in the introduction that are connected with changes in ocean productivity and may be related to the survival of salmon during the juvenile and immature life stages. The time series of BSST and SOI were obtained from H. J. Niebauer (H. J. Niebauer, University of Wisconsin, Madison, personal communication) and are described in Niebauer and Day (1989). For BSST and SOI, seasonal patterns were removed by subtracting the monthly mean temperatures (averaged over all available years) for each observation. Yearly anomalies were created by averaging the monthly anomalies for each calendar year (Figure 2). The time series for the ALPI comes from the area of low pressure (less than or equal to 100.5 kPa) located in the North Pacific Ocean over the region on 20 N to 10 N and 120 E to 120 W, is averaged for the months of December to March, and is expressed as an anomaly of the long term mean (Beamish et al. 1997). The time series ALPI was also standardized in the manner explained above (Figure 2).

Univariate time series analysis

Univariate autoregressive integrated moving average (ARIMA) modeling techniques (Box and Jenkins 1976) were used to reveal patterns and relationships in the sockeye salmon return data (see Farley and Murphy (1997) for a detailed discussion). In autoregressive (AR) processes, the present value of a time series depends on preceding values plus a random shock. In moving

average (MA) processes, random events produce an immediate effect that dissipates after short periods. Both AR and MA models require stationary time series, i.e., no trend in variance or mean values. Trends in mean values can be removed by taking successive differences of the data. Nonstationary variance can be remedied by applying a logarithmic transformation (Vandaele 1983; Quinn 1985).

A 3-phase approach for identifying and fitting ARIMA models was used (Box and Jenkins 1976): (A) model identification, (B) estimation of model parameters, and (C) diagnostics and model criticism. Time series models were identified by examining the sample autocorrelation function (SACF), sample partial autocorrelation function (SPACF), and extended sample autocorrelation function (ESACF). Time series that were nonstationary in the mean were identified when the SACF decayed very slowly and the SPACF contained a highly significant spike at lag 1. Model parameters were estimated using the maximum likelihood method. Diagnostic checks were performed to test the assumption that the residuals $\{a_t\}$ are uncorrelated random shocks with a zero mean and constant variance (Wei 1990).

In some situations, the time series in question exhibited periodic patterns. In these cases, the multiplicative model $(p,d,q) X (P,D,Q)_s$ was used where p is the order of the autoregressive model, q is the order of the moving average model, d represents the number of differences required to impose stationarity, s is the periodicity, and $P, D,$ and Q are the orders of the periodic components. Further information regarding periodic models can be found in Box and Jenkins (1976), Quinn and Marshall (1989), and Wei (1990).

Multivariate time series analysis

Multivariate models involve multiple time series and are more complex than univariate models. The approach used here was the linear transfer form (LTF) of the transfer function model described in Liu and Hanssens (1982). The linear transfer function model with one independent variable X_t can be written as:

$$(1) \quad Z_t = C + v(B)X_t + N_t$$

where $v(B) = v_0 + v_1B + v_2B^2 + \dots + v_kB^k$, $\{v_k\}$ are the transfer function weights to be estimated, B is the backshift operator defined as $B^k(Z_t) = Z_{t-k}$, C is a constant to be estimated, and N_t is the disturbance represented by an ARMA model. The representation in (1) can be extended to include multiple-inputs X_{mt} :

$$(2) \quad Z_t = C + v_1(B)X_{1t} + v_2(B)X_{2t} + \dots + v_m(B)X_{mt} + N_t$$

where m is the number of independent variables to be included in the model.

Identification of the linear transfer function model was divided into two parts: (A) estimate a set of transfer function weights, (B) determine an ARMA model for the disturbance term \hat{N}_t .

The disturbance term \hat{N}_t is estimated from the model:

$$(3) \quad \hat{N}_t = Z_t - \hat{C} - (\hat{v}_0 + \hat{v}_1 B + \hat{v}_2 B^2 + \dots + \hat{v}_k B^k) X_t$$

where $\{\hat{v}_k\}$ are initially estimated for a sufficiently large value of k assuming N_t is an

ARMA(1,0) process. Once the response weights are estimated, the model for \hat{N}_t is determined by examining the SACF and SPACF of the disturbance term.

Biological relationships used in LTF models

Linear transfer function (LTF) models were created for the return - escapement (Cushing and Ricker), sibling, and smolt relationships. If the initial noise model of the LTF model is assumed to be an ARMA(1,0), the Cushing model can be written as

$$(4) \quad \ln R_{i,a,b,t} - \phi_1 \ln R_{i,a,b,t-1} = C(1 - \phi_1) + v_k \ln E_{i,t-k} - \phi_1 v_k \ln E_{i,t-k-1} + N_t$$

where i represent the river system, a represents freshwater age, b represents marine age, and $a.b$ represents the age class. Thus, for an AR(1) noise model, returns at time t are a function of the previous year's returns and escapements (Noakes et al. 1987). The Cushing model provides density-dependence as long as v_k is less than 1. The model does not provide a maximum level of returns; returns continue to increase as escapements increase (Quinn and Deriso *in press*).

The Ricker model (Ricker 1954, 1975) offers both density-independent and density-dependent effects. The density-dependent effects may be a result of spawning stock inhibiting the population of young fish or population limits in the spawning and rearing habitats (Quinn and Deriso *in press*). By including escapement at time $t-k$ as a second independent variable and assuming an ARMA(1,0) noise model, the Ricker return and escapement model can be written as

$$(5) \quad \ln \frac{R_{i,a,b,t}}{E_{i,t-k}} - \phi_1 \ln \frac{R_{i,a,b,t-1}}{E_{i,t-k-1}} = C(1 - \phi_1) + v_k E_{i,t-k} - \phi_1 v_k E_{i,t-k-1} + N_t.$$

Sibling models relate sockeye salmon from the same brood class that mature in successive years (Bocking and Peterman 1988). Assuming an ARMA(1,0) noise model, the sibling model can be written as

$$(6) \quad \ln R_{i,a,b,t} - \phi_1 \ln R_{i,a,b,t-1} = C(1 - \phi_1) + v_2 \ln R_{i,a,b-1,t-1} - \phi_1 v_2 \ln R_{i,a,b-1,t-2} + N_t.$$

Smolt models relate the number of age 1.0 and 2.0 sockeye salmon to returning adults two (1.2 or 2.2) or three (1.3 or 2.3) years later. Assuming an ARMA(1,0) noise model, the smolt model can be written as

$$(7) \quad \ln R_{i,a,b,t} - \phi_1 \ln R_{i,a,b,t-1} = C(1 - \phi_1) + \nu_b \ln S_{i,a,0,t-b} - \phi_1 \nu_b \ln S_{i,a,0,t-b-1} + N_t$$

where S represent the number of sockeye salmon smolts.

Exploratory analysis

An exploratory analysis of cross-correlations between the white noise residuals from the univariate and multivariate time series models and the white noise residuals from the environmental models was performed to determine which environmental variables to include in the models. Cross-correlation measures the strength of an association (either positive or negative) between two time series at various lags and leads. Cross-correlating two white noise residual series performs a “test of no correlation” between the two series (Jenkins and Watts 1968). This approach may reduce the possibility of spurious correlations due to autocorrelation in the time series.

The hypothesized lagged relationships between sockeye salmon returns and environmental correlates are given in Table 1; corresponding coefficients are labeled w_k at lag k (for $k = 1$ to 6). Environmental variables were selected as possible explanatory variables when significant relationships ($\alpha = 0.05$) occurred within the hypothesized lagged relationships and when these significant relationships were consistent across age classes and river systems. If no significant relationships between sockeye salmon returns and environmental variables occurred, then the environmental variables were not included in LTF models. Significant contemporaneous relationships (lag 0) were excluded from the environmental selection and modeling process, (i.e. no w_0 term was included) because of their inapplicability to forecast models.

Model performance

Univariate and multivariate models were created using sockeye salmon age class data from 1956 to 1995 and forecasts were made for 1996 and 1997. Model performance was evaluated by comparing the coefficient of variation r^2 , residual standard error (RSE), and Schwartz’s Bayesian Information Criterion (SBC) (Wei 1990); a criterion that evaluates model parsimony. In this study, the time series do not contain the same number of observations; therefore, statistics such as RSE and SBC could not be directly compared but instead were used as ad hoc statistics during model comparison. However, since our main purpose was to evaluate model forecasts for 1996 and 1997 returns, we included percent error (PE), mean percent error (MPE) and mean absolute percent error (MAPE) for 1996 and 1997 forecasts as alternative criteria. Marshall (1992) describes the MPE as a measure of forecast bias, and the MAPE as a measure of forecast accuracy.

Forecasts for 1996 were created for each of the time series models. The time series models were then re-estimated including the data for 1996, and forecasts were created for 1997. Since the forecasts are estimated using the logarithm of returns, a bias correction factor

$$(8) \quad \hat{Z}_t = \exp(\hat{z}_t + 0.5 \hat{\sigma}^2[e_t'])$$

was used as an unbiased estimate of the forecast where \hat{Z}_t is the forecast of returns, \hat{z}_t is the natural log of the forecast, and $\hat{\sigma}^2[e_t']$ is the estimated forecast variance (Beauchamp and Olson 1973; Noakes et al. 1990).

RESULTS

Model Fitting

Examination of the SACF and SPACF showed that the time series of returns and returns per spawner for each age class within river system were stationary. The time series of escapements by river system, smolt counts for Kvichak, and all environmental series were also stationary.

Univariate Models

Univariate models of returns by age class for Egegik, Naknek, and Kvichak usually contained AR relationships with significant lag 1 parameters, suggesting that returns of sockeye salmon in year t are related to returns in the prior year (Table 2). Univariate models of returns for age classes 1.2 and 2.2 in Egegik and Kvichak contained significant AR relationships with lags that correspond to the generation length of sockeye salmon for those age classes. Periodic models were most appropriate for age class 2.3 in Egegik and age class 1.3 in Naknek where the periodic component most likely represents cycles in returns.

Fitting return per spawner data for each age class and river system yielded simpler models when compared with univariate models of returns by age class (Table 2). Six out of eight models for Egegik and Kvichak contained AR relationships with significant lag 1 parameters; three out of four Naknek models were ARIMA(0,0,0) consisting of a constant, white noise, process.

All of the univariate models for escapement contained a seasonal component of 5 years (Table 2).

The best univariate models for Kvichak smolt counts were a constant white noise process for Age 1 smolts and an autoregressive model with a significant lag 2 component for Age 2 smolts (Table 2).

Most of the environmental time series were white noise processes, (ARIMA(0,0,0) models) with the exception of BSST which contained significant AR relationships with lags 1 and 2 (ARIMA(2,0,0)).

LTF Models

The LTF Cushing and Ricker models fitted to the age class return and return per spawner series for Egegik, Naknek, and Kvichak are shown in Table 3. Five out of eight of the disturbance terms for Egegik and Kvichak contained a significant AR relationship at lag 1; whereas three out of four of the disturbance terms for Naknek were simple white noise processes. The escapement parameters for the Cushing model were significant for all of the models except Naknek age class 2.2. Significant escapement parameters for the Cushing model were generally close to or greater than 1. Egegik age class 1.3, Naknek age classes 2.2 and 2.3, and Kvichak age classes 1.2 and 1.3 contained significant escapement parameters for the Ricker model. In many of the Cushing and Ricker models, the productivity parameter ($c(1-\phi)$) was not significant.

All of the disturbance terms for the LTF sibling models, except for age class 1.3 in Naknek, were simple white noise processes (Table 3). The parameter relating a cohort of the previous year to returns for each sibling relationship was highly significant in all of the models, suggesting a strong connection between returns of a brood class the previous year.

Significant relationships between returns of sockeye salmon and smolt were found for each age class in Kvichak (Table 3). The constant parameter ($c(1-\phi)$) was not significant for sockeye salmon that remained two years in the ocean and significant for sockeye salmon that remained 3 years in the ocean.

Exploratory Analyses

Cold Bay air temperature (CBMAT) was the only environmental variable consistently retained in univariate and LTF time series models. Most of the significant relationships with KSAJT, SOI, ALPI and BSST were either contemporaneous or the significant relationships were not consistent between age classes or river systems. Therefore, only results of the CBMAT correlations are presented (Table 4).

There were more significant relationships between returns of sockeye salmon and CBMAT than with models that included escapement data and CBMAT. For E-Return models that included CBMAT, the models for the noise generally compared with univariate models of returns (U-Return). The addition of CBMAT to spawner-recruit relationships usually simplified the noise models, reducing the noise model to an ARMA(0,0).

CBMAT parameter estimates were usually positive suggesting that warmer air temperatures from May through August in Cold Bay, Alaska were related to larger returns of sockeye salmon to Egegik, Naknek, and Kvichak Rivers. Significant cross-correlations between CBMAT and the return data generally occurred at lags 1 or 2 for age classes 1.2 and 2.2 and lags 1, 2, or 3 for age classes 1.3 and 2.3 implying that air temperatures at Cold Bay during May through August affect sockeye salmon survival at the juvenile and immature life stages.

Model Performance

The best model and forecast statistics for 2-ocean sockeye salmon consisted of age class returns (1.2 and 2.2) that included CBMAT (E-Return), whereas, sibling models produced the best model and forecast statistics for most of the 3-ocean sockeye salmon return time series, (Figures 3 and 4). The only exceptions were for age classes 2.2 and 2.3 in Kvichak where the LTF smolt model and univariate model of returns (U-Return) produced the best overall model and forecast statistics, respectively. In most instances, MPE was positive and nearly equal to MAPE indicating a bias toward over-forecasting by the time series models (Figure 4).

Although the models presented above produced the best overall model and forecast statistics, they nevertheless resulted in inaccurate forecasts (Figure 5). The environmental models for 1996 severely over-forecast returns for age classes 1.2 and 2.2 in 1996, implying that the environmental information was not a good indicator of the decline in sockeye salmon returns for these age classes. The 1996 forecasts produced by the sibling models for age classes 1.3 and 2.3 tended to be more accurate, under-forecasting returns for these age classes in Egegik and Naknek and slightly over-forecasting returns in Kvichak. Overall, forecast error improved for 2-ocean sockeye salmon models that incorporated the environment during 1997 when compared to 1996. For 3-ocean sockeye salmon returns, forecast error remained the same in Egegik, slightly under-forecasting returns of 3-ocean sockeye salmon; however, forecast error increased for models that incorporated sibling data in Naknek and Kvichak, over-forecasting returns of 3-ocean sockeye salmon to these rivers.

DISCUSSION

By examining the age class returns of sockeye salmon to Egegik, Naknek, and Kvichak Rivers, we established a pattern of lower than expected returns across river systems beginning with returns of 2-ocean sockeye salmon during 1996 and extending to all age classes in Naknek and Kvichak Rivers during 1997. These patterns were revealed by the tendency of the forecast models to over-forecast returns of 2-ocean sockeye salmon returning to these three rivers during 1996 and to over-forecast returns for all age classes of sockeye salmon returning to the Naknek and Kvichak Rivers during 1997.

The strong similarity of these forecast patterns across river systems may indicate common events affecting either freshwater or marine survival. We found evidence of common influence with air temperatures at Cold Bay, Alaska between May and August and ocean survival of Bristol Bay sockeye salmon at the juvenile and immature life history stages. The addition of Cold Bay air temperatures to forecast models did not explain the sudden decrease in sockeye salmon returns during 1996, but did improve forecast performance for returns of 2-ocean sockeye salmon during 1997.

The best-fit linear transfer function models for sockeye salmon returning to Egegik, Naknek, and Kvichak Rivers occur with air temperatures during the juvenile and immature life

history stage. It is believed that salmon survival may be significantly impacted by marine climate variability early in the ocean phases of their life cycles (Pearcy 1992; Hare 1996). During 1996, there was an absence of 2-ocean sockeye salmon returning to Bristol Bay; however, returns of 3-ocean sockeye salmon actually exceeded expectations. During 1997, there was an apparent drop in expected returns for most age classes particularly in Naknek and Kvichak. If survival of sockeye salmon is impacted early in their marine life history stage, then this suggests a change in the marine environment beginning in 1994 affecting 2-ocean sockeye salmon returning in 1996 and continuing through 1995 affecting all age classes returning in 1997.

Abrupt changes in climate indices, such as the Pacific (inter)Decadal Oscillation, or PDO, have been linked to changes in salmon productivity (Mantua et al. 1997). A characteristic of the PDO is a recurring pattern of interdecadal climate variability, characterized by positive or negative phases, which appear to resemble large interdecadal fluctuations in Alaskan salmon abundance. The current phase of the PDO is positive implying favorable ocean conditions (Hare et al. *in press*). If this is true, then the recent decline in sockeye salmon production to Bristol Bay may not be related to a major shift in ocean conditions. Evidence of this is in Figure 1 where returns of sockeye salmon during 1996 and 1997, seem to be within or near the range of sockeye salmon returns to Bristol Bay for the past 20 years.

Hence, the dramatic decline in sockeye salmon returns to Egegik, Naknek, and Kvichak Rivers during 1996 and 1997 may be a temporary change in returns. In an analysis of outliers within sockeye salmon catch time series, Farley and Murphy (1997) found temporary changes in catch for western Alaska river systems that may have been related to cold winter temperatures. In this analysis, we found a positive relationship between air temperatures taken at Cold Bay, Alaska during May through August and survival at the juvenile and immature life history stages of Bristol Bay sockeye salmon. However, there is no indication in the time series of air temperatures of an abrupt period of colder temperatures in recent years.

Conclusions

1. Returns of 2-ocean sockeye salmon to Egegik, Naknek, and Kvichak were anomalously low during 1996. The unexpected low returns persisted into 1997 and included all age classes, particularly in Naknek and Kvichak Rivers. Some of the climate indices show a decline beginning in 1994, which would have affected early marine survival of sockeye salmon returning during 1996, but it is uncertain whether the lower sockeye salmon returns will persist into the future.
2. There was a positive relationship between CBMAT and survival of sockeye salmon at the juvenile and immature life history stages. Including CBMAT in forecast models produced the best model and forecast statistics for 2-ocean sockeye salmon returns; however, the environmental models produced large over-forecast error, particularly for Naknek and Kvichak Rivers, implying CBMAT was not a good predictor of declining sockeye salmon returns.
3. There is a strong relationship between returns of 3-ocean sockeye salmon and 2-ocean sockeye salmon returning the previous year. Sibling relationships produced the best model and

forecast statistics for returns of 3-ocean sockeye salmon and were particularly useful for explaining returns of 3-ocean sockeye salmon to the Egegik River, slightly under-forecasting returns during 1996 and 1997.

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LITERATURE CITED

- Adkison, M. D., R. M. Peterman, M. F. Lapointe, D. M. Gillis, and J. Korman. 1996. Alternative models of climatic effects on sockeye salmon (*Oncorhynchus nerka*) productivity in Bristol Bay, Alaska and Fraser, River, British Columbia. *Fisheries Oceanography* 5:137-152.
- Beamish, R.J., and D.R. Bouillon. 1995. Marine fish production trends off the Pacific coast of Canada and the United States. Pages 565-591 in R.J. Beamish, [ed.] *Climate change and northern fish populations*. Canadian Special Publication of Fisheries and Aquatic Sciences 121.
- Beamish, R.J., G.A. McFarlane, D. Noakes, M. Folkes, V.V. Ivanov, and V. Kurashov. A comparison of the Aleutian Low Pressure Index and the Atmospheric Circulation Index as indices of Pacific salmon abundance trends. (NPAFC Doc. 289). 25 p. Department of Fisheries and Oceans, Pacific Biological Station, Nanaimo, B.C. Canada. V9R 5K6.
- Beamish, R.J., C-E.M. Neville, and A.J. Cass. 1997. Production of Fraser River sockeye salmon (*Oncorhynchus nerka*) in relation to decadal-scale changes in the climate and the ocean. *Canadian Journal of Fisheries and Aquatic Sciences* 54:543-554.
- Beauchamp, J.J., and J.S. Olson. 1973. Correction for bias in regression estimates after logarithmic transformations. *Ecology* 54:1403-1407.
- Bocking, R.C., and R.M. Peterman. 1988. Preseason forecasts of sockeye salmon (*Oncorhynchus nerka*): comparison of methods and economic considerations. *Canadian Journal of Fisheries and Aquatic Sciences* 45:1346-1354.
- Box, G.E.P., and G.M. Jenkins. 1976. *Time Series Analysis: Forecasting and Control*, 2nd ed. Holden-Day, San Francisco, California.
- Farley, E.V. Jr. 1996. Time series analysis forecasts for sockeye salmon (*Oncorhynchus nerka*) in the Egegik, Naknek, and Kvichak Rivers of Bristol Bay, Alaska. Masters Thesis, University of Alaska, Fairbanks.
- Farley, E. V. and J. M. Murphy. 1997. Time series outlier analysis: Evidence for management and environmental influences on sockeye salmon catches in Alaska and northern British Columbia. *Alaska Fishery Research Bulletin* 4(1):36-53.
- Francis, R.C., and S.R. Hare. 1994. Decadal-scale regime shifts in the large marine ecosystems of the north-east Pacific: a case for historical science. *Fisheries Oceanography* 3:279-291.

- Hare, S.R., and R.C. Francis. 1995. Climate change and salmon production in the northeast Pacific Ocean. Pages 357-372 in R. J. Beamish, [ed.] Climate Change and Northern Fish Populations. Canadian Special Publication of Fisheries and Aquatic Sciences 121.
- Hare, S.R., N.J. Mantua, and R.C. Francis. (*in press*). Inverse production regimes: Alaska and West Coast Pacific salmon. Fisheries.
- Hare, S.R. 1996. Low frequency climate variability and salmon production. Ph.D. dissertation, School of Fisheries, University of Washington. 306 pp.
- Jenkins, G.M. and D.G. Watts. 1968. Spectral Analysis and its Applications. Holden-Day, San Francisco, CA. 525 p.
- Koo, T.S.Y. 1962. Age designation in salmon. p. 37-48. In T.S.Y. Koo [ed.] Studies of Alaska red salmon. University of Washington Publications in Fisheries, New Series, Volume I.
- Liu, L.M., and D.M. Hanssens. 1982. Identification of multiple-input transfer function models. Communication in Statistics 11:297-314.
- Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis. 1997. A Pacific-interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78:1069-1079.
- Marshall, R. P. 1992. Forecasting catches of Pacific salmon in commercial fisheries of Southeast Alaska. PHD dissertation, University of Alaska-Fairbanks, Fairbanks, AK. 264 p.
- Mysak, L.A. 1986. El Niño, interannual variability and fisheries in the northeast Pacific Ocean. Canadian Journal of Fisheries and Aquatic Sciences 43:464-497.
- Niebauer, H.J., and R.H. Day. 1989. Causes of interannual variability in the sea ice cover of the eastern Bering Sea. GeoJournal 18:45-59.
- Noakes, D. J., D. W. Welch, and M. Stocker. 1987. A time series approach to stock-recruitment analysis: transfer function noise modeling. Natural Resource Modeling. 2(2):213-233.
- Noakes, D. J., D. W. Welch, M. Henderson, and E. Mansfield. 1990. A comparison of preseason forecasting methods for returns of two British Columbia sockeye salmon stocks. North. Amer. J. Fish. Man. 10:46-57.
- Pearcy, W.G. 1992. Ocean ecology of North Pacific salmonids. University of Washington Press, Seattle.

- Peterman, R.M. 1987. Review of the components of recruitment of Pacific salmon. *in* Common Strategies of Anadromous and Catadromous Fishes. M. Dadswell, R. Klauda, C. Moffitt, R. Saunders, R. Rulifson and J.E. Cooper [ed.] American Fisheries Society Symposium 1:417-429.
- Quinn II, T. J., and R. B. Deriso. (*in Press*). Quantitative Fish Dynamics. Oxford University Press, New York.
- Quinn II, T. J. 1985. Catch-per-unit-effort: a statistical model for Pacific halibut. Canadian Journal of Fisheries and Aquatic Sciences 42:1423-1429.
- Quinn II, T. J., and R. P. Marshall. 1989. Time series analysis: Quantifying variability and correlation in SE Alaska salmon catches and environmental data. Canadian Special Publication of Fisheries and Aquatic Sciences 108:67-80.
- Ricker, W.E. 1954. Stock and recruitment. Journal of Fisheries Research Board Canada 11:559-623.
- Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin of the Fisheries Research Board Canada 191.
- Schwartz, G. 1978. Estimating the dimension of a model. Ann. Statist., 6:461-464.
- Straty, R.R., and H.W. Jaenicke. 1980. Estuarine influence of salinity, temperature, and food on the behavior, growth, and dynamics of Bristol Bay sockeye salmon. P. 247-265 *in* W.J. McNeil and D.C. Himsworth [ed.], Salmonid ecosystems of the North Pacific, Oregon State University Press, Corvallis 331 p.
- Vandaele, W. 1983. Applied Time Series Analysis and Box-Jenkins Models. Academic Press, Orlando, FL. 417 p.
- Wei, W. W. S. 1990. Time Series Analysis: Univariate and Multivariate Methods. Addison-Wesley Publishing Company, Inc., CA. 478 p.

Age Classes 1.2

Lag

	KSAJT	CBMAT	BSST	SOI	ALPI
1	*	*	*	*	*
2	*	*	*	*	*
3				*	*
4				*	*

Age Classes 1.3

Lag

	KSAJT	CBMAT	BSST	SOI	ALPI
1	*	*	*	*	*
2	*	*	*	*	*
3	*	*	*	*	*
4				*	*
5				*	*

Age Classes 2.2

Lag

	KSAJT	CBMAT	BSST	SOI	ALPI
1	*	*	*	*	*
2	*	*	*	*	*
3				*	*
4				*	*
5				*	*

Age Classes 2.3

Lag

	KSAJT	CBMAT	BSST	SOI	ALPI
1	*	*	*	*	*
2	*	*	*	*	*
3	*	*	*	*	*
4				*	*
5				*	*
6				*	*

Table 2. Univariate time series models of returns, returns/spawner, escapement, and smolt (Kvichak only) for Egegik, Naknek, and Kvichak sockeye salmon stocks by age class.

Time Series	River System	Age Class			
		1.2	1.3	2.2	2.3
<u>Return</u>					
	Egegik	(4,0,0) $\phi_{2,3}=0$	(3,0,0) $\phi_{2=0}$	(5,0,0) $\phi_{1,3,4=0}$	(1,0,0)(1,0,0) ₆
	Naknek	(2,0,0)	(1,0,0)(1,0,0) ₅	(0,0,0)	(0,0,0)
	Kvichak	(4,0,0) $\phi_{2,3}=0$	(4,0,0) $\phi_{2,3=0}$	(5,0,0) $\phi_{1-4=0}$	(5,0,1) $\phi_{1-3=0}$
<u>Return/ Spawner</u>					
	Egegik	(1,0,0)	(1,0,0)	(2,0,0) $\phi_1=0$	(1,0,0)
	Naknek	(0,0,0)	(5,0,0) $\phi_{1-4}=0$	(0,0,0)	(0,0,0)
	Kvichak	(1,0,0)	(1,0,0)	(1,0,0)	(0,0,0)
<u>Escapement</u>					
	Egegik		(1,0,0)(1,0,0) ₅		
	Naknek		(1,0,0)(1,0,0) ₅		
	Kvichak		(1,0,0)(1,0,0) ₅		
<u>Smolt</u>					
	Kvichak (Age I)		(0,0,0)		
	Kvichak (Age II)		(2,0,0) $\phi_1=0$		

Table 3. LTF Cushing, Ricker, Sibling, and Smolt (Kvichak only) time series models for Egegik, Naknek, and Kvichak logarithm of returns for age classes 1.2, 1.3, 2.2, and 2.3 and logarithm of escapement (1956-1995) and logarithm of smolt age I and II for Kvichak (1976-1995) with parameter estimates and t-values (in parenthesis). Dash (-) indicates non-significant parameter.

Model	River System	Parameter Estimate	1.2	1.3	2.2	2.3
<u>Cushing</u>	Egegik	C(1- ϕ)	-	-	-	-
		v_k	0.88 (29.2)	0.92 (30.9)	1.06 (53.7)	1.02 (61.9)
		AR	$\phi_1=0.59$ (4.5)	$\phi_1=0.57$ (4.2)	$\phi_2=0.57$ (4.0)	$\phi_1=0.40$ (2.5)
		MA	-	-	-	-
	Naknek	C(1- ϕ)	-	-	10.3 (2.0)	5.6 (1.9)
		v_k	0.92 (90.6)	0.99 (60.4)	0.21 (0.5)	0.57 (2.6)
		AR	-	$\phi_5=0.37$ (2.2)	-	-
		MA	-	-	-	-
	Kvichak	C(1- ϕ)	5.3 (1.9)	8.53 (3.4)	-	-
		v_k	0.56 (3.1)	0.30 (1.8)	0.99 (89.1)	0.87 (71.6)
		AR	$\phi_1=0.48$ (3.2)	$\phi_1=0.50$ (3.4)	-	-
		MA	-	-	-	-
<u>Ricker</u>	Egegik	C(1- ϕ)	-1.24 (-2.0)	-	0.74 (1.8)	-
		v_k	$-0.30E^{-6}$ (-0.8)	$-0.82E^{-6}$ (-2.6)	$0.78E^{-7}$ (0.3)	$0.10E^{-6}$ (0.5)
		AR	$\phi_1=0.63$ (4.6)	$\phi_1=0.63$ (4.9)	$\phi_2=0.57$ (3.8)	$\phi_1=0.40$ (2.5)
		MA	-	-	-	-
	Naknek	C(1- ϕ)	-0.78 (-2.71)	-	-	-
		v_k	$-0.27E^{-6}$ (-1.3)	$-0.18E^{-6}$ (-0.9)	$-0.58E^{-6}$ (-3.8)	$-0.36E^{-6}$ (-4.1)
		AR	-	$\Phi^a_1=0.33$ (1.9)	-	-
		MA	-	$\Phi^a_5=0.37$ (2.3)	-	-
	Kvichak	C(1- ϕ)	-0.94 (-2.2)	-1.31 (-3.3)	-	-1.70 (-6.6)
		v_k	$-0.69E^{-7}$ (-2.2)	$-0.16E^{-6}$ (-4.0)	$0.22E^{-7}$ (1.0)	$-0.48E^{-7}$ (-1.5)
		AR	$\phi_1=0.58$ (3.2)	$\phi_1=0.58$ (3.4)	$\phi_1=0.39$ (2.4)	-
		MA	-	-	-	-
<u>Sibling</u>	Egegik	C(1- ϕ)	-	2.05 (2.4)	-	3.83 (3.0)
		v_l	-	0.88 (12.7)	-	0.70 (7.8)
		AR	-	-	-	-
		MA	-	-	-	-
	Naknek	C(1- ϕ)	-	5.61 (4.0)	-	9.30 (7.4)
		v_l	-	0.63 (5.7)	-	0.31 (3.2)
		AR	-	$\phi_1=0.31$ (2.1)	-	-
		MA	-	-	-	-
	Kvichak	C(1- ϕ)	-	2.22 (2.2)	-	-
		v_l	-	0.79 (11.1)	-	0.86 (38.5)
		AR	-	-	-	-
		MA	-	-	-	-

Table 3 (con't). LTF Cushing, Ricker, Sibling, and Smolt time series models for Egegik, Naknek, and Kvichak logarithm of returns for age classes 1.2, 1.3, 2.2, and 2.3 and logarithm of escapement (1956-1995) and logarithm of smolt age I and II for Kvichak (1976-1995) with parameter estimates and t-values (in parenthesis).

Model	River System	Parameter Estimate	1.2	1.3	2.2	2.3
<u>Smolt</u>	Kvichak	C(1- ϕ)	-	8.60 (3.9)	-	6.58 (2.4)
		v_b	0.83 (125.3)	0.31 (2.5)	0.87 (78.7)	0.39 (2.5)
		AR	$\phi_1=-0.53$ (-2.5)	-	-	-
		MA	-	-	-	-

a) Φ_1 and Φ_5 are multiplicative autoregressive coefficients for the periodic noise model

Table 4. LTF models of environment for Egegik, Naknek, and Kvichak sockeye salmon age classes 1.2, 1.3, 2.2, and 2.3 with parameter estimates and t-values (in parenthesis). Dash (-) indicates non-significant parameter.

Model	River System	Parameter Estimate	1.2	1.3	2.2	2.3
<u>E-Return</u> ¹	Egegik	C(1- ϕ)	13.13 (12.3)	-	14.46 (47.3)	-
		w_1	0.22 (2.0)	-	-	-
		w_2	0.22 (2.1)	-	0.53 (5.2)	-
		w_3	-	-	-	-
		AR	$\phi_1=0.47$ (3.7) $\phi_4=0.38$ (3.5)	-	$\phi_1=0.63$ (4.9)	-
		MA	-	-	-	-
	Naknek	C(1- ϕ)	12.96 (159.6)	13.79 (48.4)	13.17 (72.9)	-
		w_1	0.24 (2.4)	-	-	-
		w_2	0.41 (4.0)	-	0.37 (2.1)	-
		w_3	-	0.34 (3.6)	-	-
		AR	$\phi_2=0.37$ (2.2)	$\phi_5=0.55$ (3.5)	-	-
		MA	-	-	-	-
	Kvichak	C(1- ϕ)	13.84 (59.6)	13.07 (37.1)	15.34 (21.1)	-
		w_1	0.71 (5.6)	-	-	-
		w_2	0.47 (3.6)	0.38 (1.9)	0.27 (1.8)	-
		w_3	-	-	-	-
		AR	$\phi_4=0.52$ (4.3)	$\phi_1=0.42$ (2.8)	$\phi_5=0.69$ (5.5)	-
		MA	$\theta_2=0.35$ (2.2)	-	-	-
<u>E-R/S</u> ²	Egegik	C(1- ϕ)	-	-	0.71 (3.2)	-
		w_1	-	-	-	-
		w_2	-	-	0.43 (4.5)	-
		w_3	-	-	-	-
		AR	-	-	$\phi_1=0.54$ (3.6)	-
		MA	-	-	-	-
	Naknek	C(1- ϕ)	-1.09 (-8.6)	-0.28 (-2.3)	-	-
		w_1	-	-	-	-
		w_2	0.39 (3.3)	-	-	-
		w_3	-	0.43 (3.7)	-	-
		AR	-	-	-	-
		MA	-	-	-	-
	Kvichak	C(1- ϕ)	-	-	-	-2.02 (-10.8)
		w_1	-	-	-	0.40 (2.3)
		w_2	-	-	-	-
		w_3	-	-	-	-
		AR	-	-	-	-
		MA	-	-	-	-

¹ LTF model of returns that includes CBMAT

² LTF model of returns per spawner that includes CBMAT

Table 4 (con't). LTF models of environment for Egegik, Naknek, and Kvichak sockeye salmon age classes 1.2, 1.3, 2.2, and 2.3 with parameter estimates and t-values (in parenthesis). Dash (-) indicates non-significant parameter.

Model	River System	Parameter Estimate	1.2	1.3	2.2	2.3
<u>E-Cushing</u> ³	Egegik	C(1- ϕ)	-	-	-	-
		w_1	-	-	-	-
		w_2	-	-	0.42 (4.5)	-
		w_3	-	-	-	-
		V_k	-	-	1.05 (72.5)	-
		AR	-	-	$\phi_1=0.50$ (3.5)	-
		MA	-	-	-	-
	Naknek	C(1- ϕ)	-	-	-	-
		w_1	-	-	-	-
		w_2	-	-	-	-
		w_3	-	0.34 (3.6)	-	-
		V_k	-	0.99 (78.3)	-	-
		AR	-	$\phi_5=0.33$ (1.9)	-	-
		MA	-	-	-	-
	Kvichak	C(1- ϕ)	-	-	-	-
		w_1	-	-	-	0.41 (2.6)
		w_2	-	-	0.31 (2.0)	-
		w_3	-	-	-	-
		V_k	-	-	0.99 (94.2)	0.87 (78.5)
		AR	-	-	-	-
		MA	-	-	-	-

³ LTF Cushing model that includes CBMAT

Table 4 (con't). LTF models of environment for Egegik, Naknek, and Kvichak sockeye salmon age classes 1.2, 1.3, 2.2, and 2.3 with parameter estimates and t-values (in parenthesis). Dash (-) indicates non-significant parameter.

Model	River System	Parameter Estimate	1.2	1.3	2.2	2.3	
<u>E-Ricker</u> ⁴	Egegik	C(1- ϕ)	-	-	0.54 (1.5)	-	
		w_1	-	-	-	-	
		w_2	-	-	0.41 (4.3)	-	
		w_3	-	-	-	-	
		V_k	-	-	0.16E ⁻⁶ (0.6)	-	
		AR	-	-	$\phi_1=0.51$ (3.3)	-	
		MA	-	-	-	-	
	Naknek	C(1- ϕ)	-0.60 (-2.5)	-	-	-	-
		w_1	-	-	-	-	
		w_2	0.42 (3.7)	-	-	-	
		w_3	-	0.43 (3.7)	-	-	
		V_k	-0.40E ⁻⁶ (-2.3)	-0.21E ⁻⁶ (-2.1)	-	-	
		AR	-	-	-	-	
		MA	-	-	-	-	
	Kvichak	C(1- ϕ)	-	-	-	-	
		w_1	-	-	-	-	
		w_2	-	-	-	-	
		w_3	-	-	-	-	
		V_k	-	-	-	-	
		AR	-	-	-	-	
		MA	-	-	-	-	

⁴ LTF Ricker model that includes CBMAT

Table 5. Explanation of model notation.

Model	Explanation
U-Return	Univariate model of Returns
U-R/S	Univariate model of Returns per escapement
E-Return	LTF model of Returns that includes CBMAT
E-R/S	LTF model of Returns per escapement that includes CBMAT
Ricker	LTF Ricker model
E-Ricker	LTF Ricker model that includes CBMAT
Cushing	LTF Cushing model
E-Cushing	LTF Cushing model that includes CBMAT
Sibling	LTF sibling model

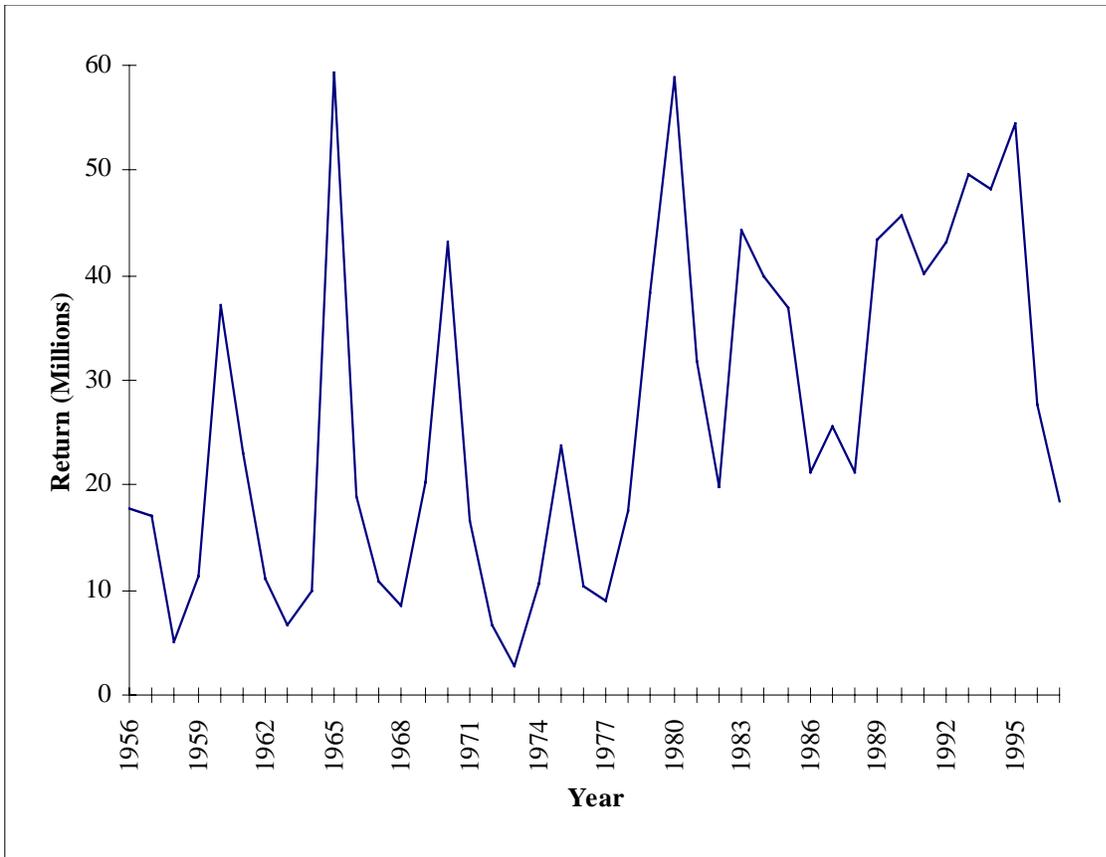


Figure 1. Total return (millions) of sockeye salmon to Bristol Bay, Alaska (1956 - 1997).

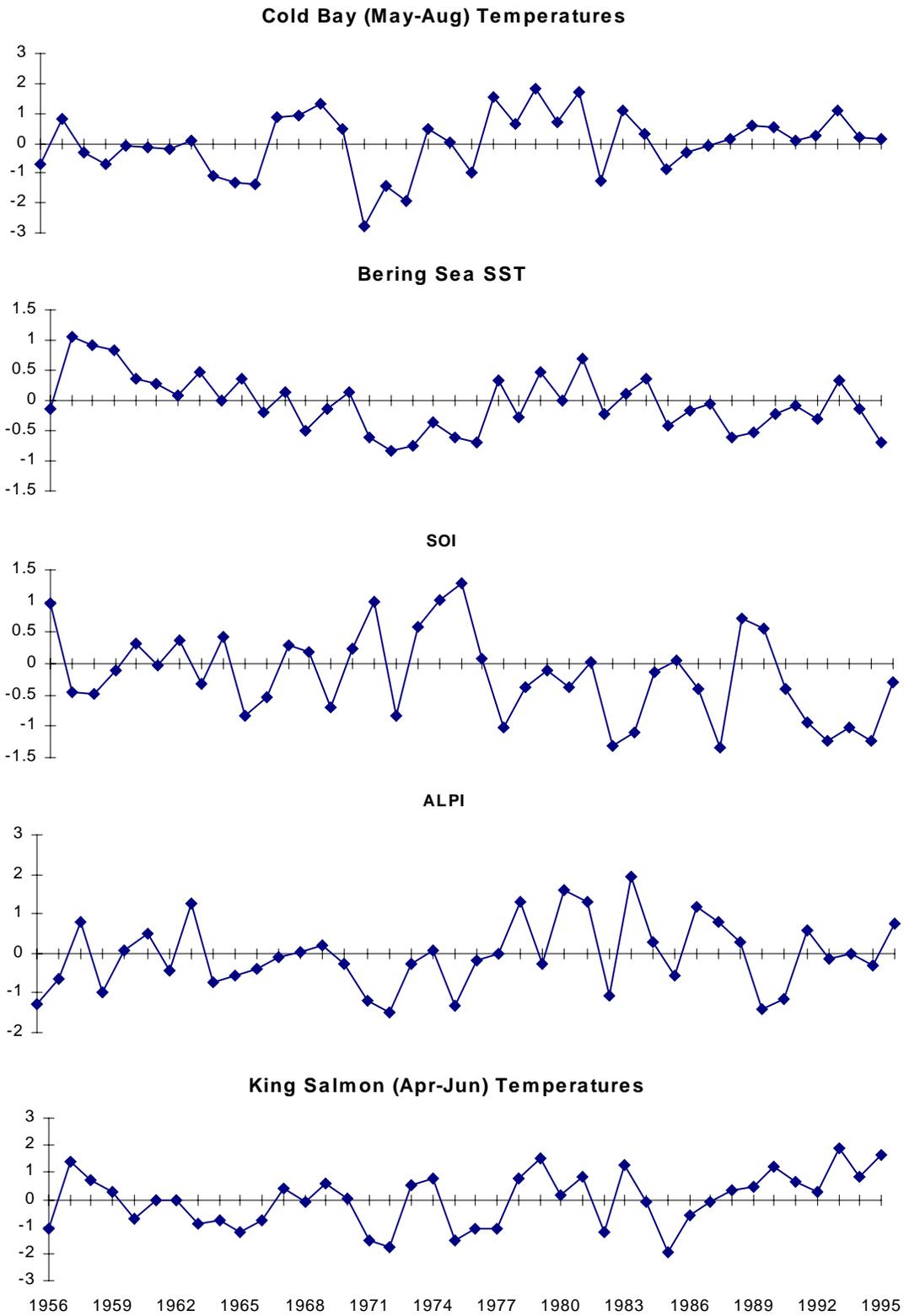


Figure 2. Time series of climatological data (1956 - 1995).

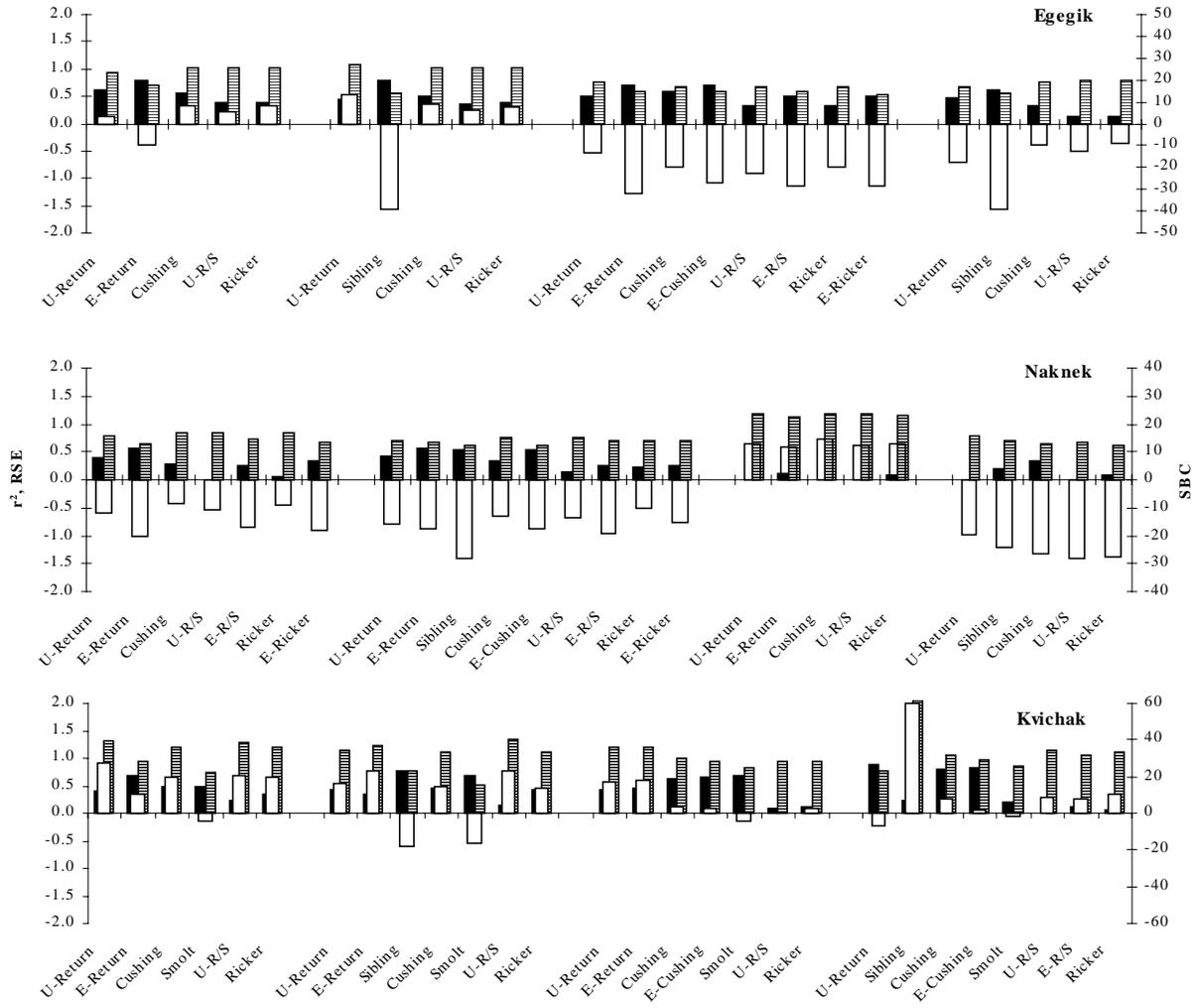


Figure 3. Residual Standard Error (RSE; striped), Schwarz's Bayesian Criterion (SBC; clear), and the coefficient of variation r^2 (solid) for each time series model and age class for Egegik, Naknek, and Kvichak sockeye salmon stocks.

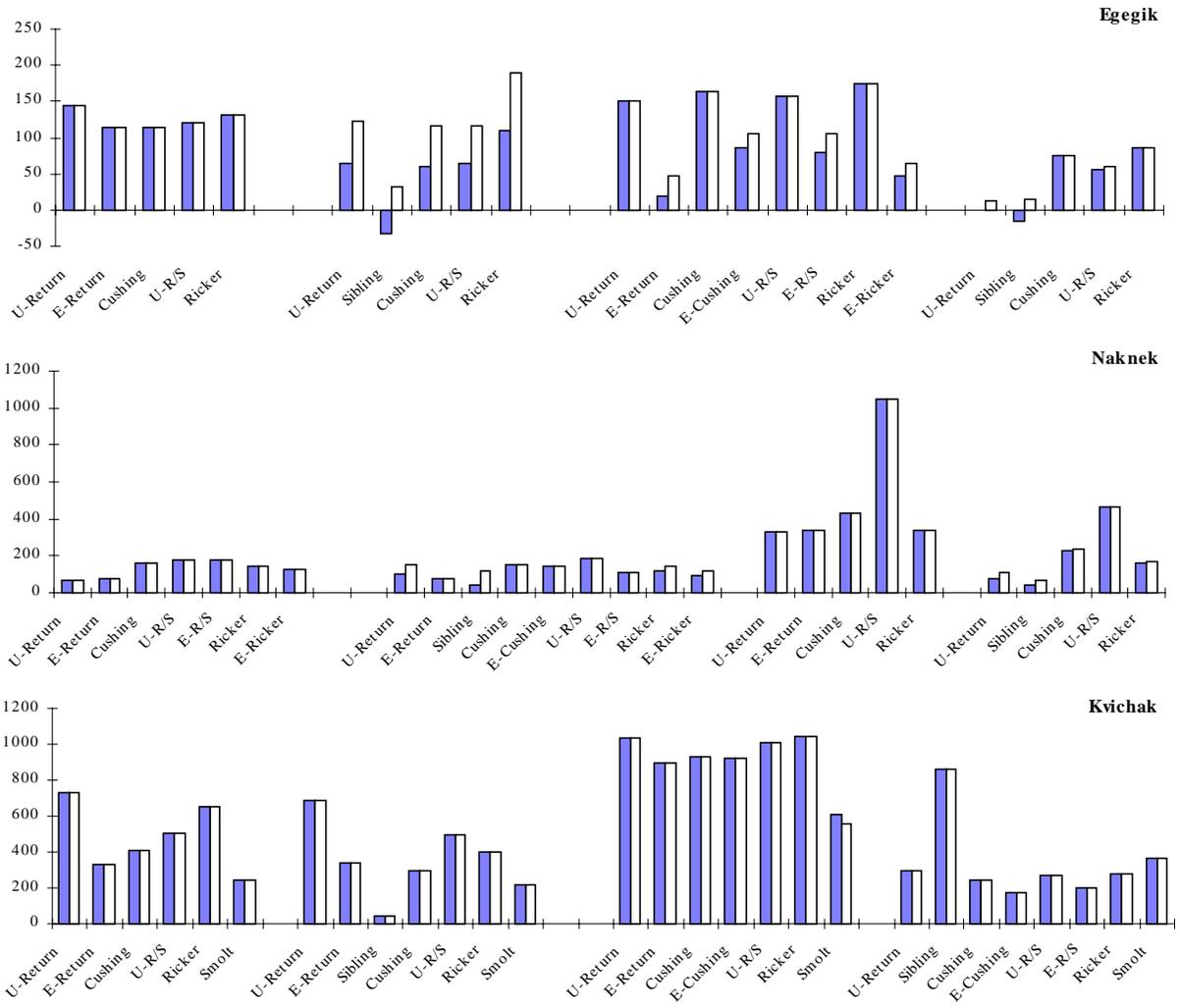
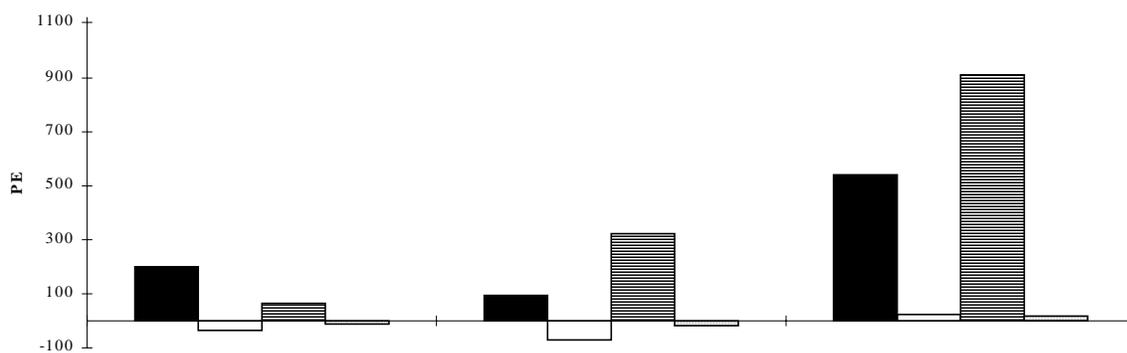


Figure 4. Mean percent error (MPE; solid) and mean absolute percent error (MAPE; clear) for each time series model and age class for Egegik, Naknek, and Kvichak sockeye salmon stocks for 1996 and 1997.

1996



1997

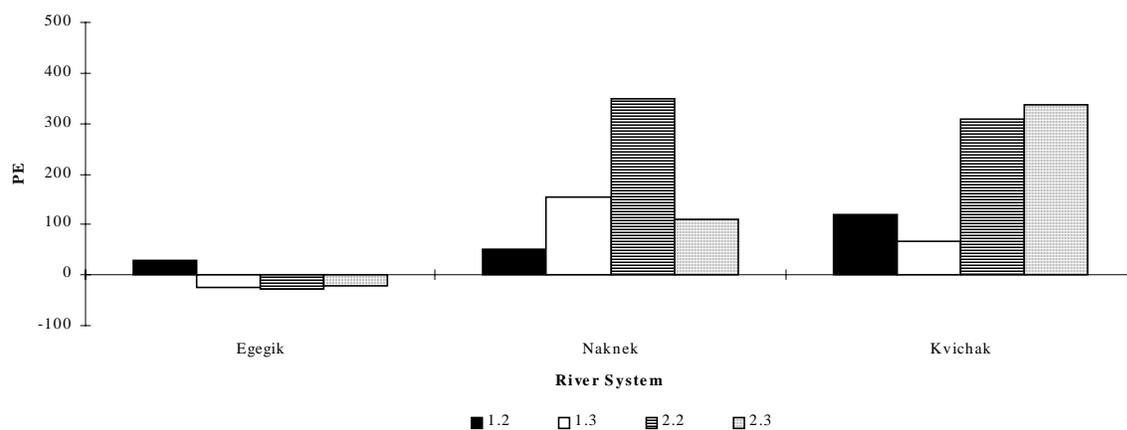


Figure 5. Percent error (PE) during 1996 and 1997 for selected time series models for Egegik (E-Return:2-ocean; Sibling:3-ocean), Naknek (E-Return:2-ocean; Sibling:3-ocean), and Kvichak (E-Return:1.2; Sibling:1.3; Smolt:2.2; U-Return:2.3) sockeye salmon stocks.